

Ludendorff Coronal Flattening Index of the Total Solar Eclipse on March 9, 2016

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Abstract. Ludendorff coronal flattening index of the Total Solar Eclipse (TSE) on March 9, 2016, was calculated at various distances in solar radius. As a result, we obtained the coronal flattening index ($\epsilon = a + b$) at a distance of 2 solar radii is 0.16. The 24th solar cycle phase based on the 2016 TSE event obtained -0.64 which showed the corona is pre-minimum type. Resulted coronal flattening index value gives a predicted maximum amplitude of the monthly sunspot number (W_{max}) for the 25th solar cycle to be 70 ± 65 . Therefore, the solar activity for 25th solar cycle predicted to be lower than the current solar cycle, which has a maximum sunspot number value of 146 in February 2014

1. Introduction

Space-based observations provide opportunity to study the physics of solar corona [1], but ground-based observations conducted during total solar eclipses give another chances to understand the lower part of corona [2] since the global and local magnetic field of the sun inner part influenced the solar coronal shapes. Consequently, the structure will change according to the solar cycle. Corona at minimum solar activity has asymmetrical brightness distribution characteristics around the solar disc with two very bright streamers around the equator. While corona at maximum solar activity has characteristics of uniform brightness with the streamer around the sun [3]. Photometry of the K and F corona observed using the white-light filter during TSE events [4]. K-corona is the photosphere light scattered by the free electron gas in the corona while F-corona is the photosphere light scattered by dust particles of small size in the ecliptic plane [5].

One way to quantify the global structure of the corona is using Ludendorff coronal flattening index (ϵ) [6]. Several studies calculated coronal flattening index for TSE event have been conducted [7, 4, 3, 8, 6, 9]. From the compilation of measurements, variation of coronal flattening index over solar cycle can be modeled and the characteristics of upcoming solar cycle (e.g. time of maximum and the amplitude) can be predicted [8]. In this study, we obtained coronal flattening index by analyzed the solar image isophotes during totality on the 2016 TSE. Henceforth, the sunspot number maximum amplitude for the next solar cycle is predicted using the coronal flattening index. In addition, the type of corona determined based on the current solar cycle phase.

2. Data and Method

We conducted the 2016 TSE observation at Ngata Baru ($0^{\circ}55'27''$ South, $119^{\circ}57'27''$ East, $320m$ asl.), Central Sulawesi, Indonesia. At this point, the duration of totality is 2m 14s while the general sky condition was clear. Four images were acquired using 12 Mpx camera with various field of views and exposure times. All these images were captured using ISO 800 setting with exposure from $1/60s$, $1/100s$, $1/160s$, and $1/200s$. Taken from 07:39:17 until 07:40:41 local time.

No special data reduction was applied, but the images were rotated to get the proper orientation and matched with reference images (SDO/AIA 193 from <http://sdo.gsfc.nasa.gov> and SOHO/LASCO C2 from <http://sohodata/nascom.nasa.gov>). Observed features such as prominence and streamer became visual guides for the matching process. Additional data of monthly sunspot number from WDC-SILSO from Royal Observatory of Belgium (<http://www.sidc.be/silso>) and multi-year forecast sunspot number from SWPC NOAA (<http://www.swpc.noaa.gov>) was used to determine the phase of current solar cycle.

Ludendorff flattening index was determined from the isophotal contours (isophote in brief) with various equatorial distances from the limb. The isophote was constructed for each grayscale images that was properly oriented to the solar equator. Image with different exposures enable us to construct several sets of isophote that give the value of flattening indexes at various distances. The flattening index itself is defined as

$$\epsilon = \frac{d_0 + d_1 + d_2}{D_0 + D_1 + D_2} - 1 \quad (1)$$

where d_0 is the diameter of isophote at the equator, d_1 and d_2 is the diameter at an angle of $\pm 22.5^{\circ}$ axis parallel to the equator. While D_0 , D_1 , and D_2 is the diameter isophote in the polar axis direction. The value of ϵ increase linearly from the limb to a certain distance, $R_{max} = 1.5 - 2.5 R_{sun}$ then decrease up to a distance $R_{min} = 3.5 - 5.5 R_{sun}$. Ludendorff (and the citing authors) use ϵ at $r = 2 R_{sun}$ as the photometric flattening index. To obtain this number, extrapolation is often used since the low intensity of the outer part of the solar corona.

The value of ϵ is also a function of the solar cycle phase (Φ) as introduced by [10] with following equation:

$$\Phi = \frac{T_{ecl} - T_{min}}{|T_{max} - T_{min}|} \quad (2)$$

where T_{ecl} is the time of the eclipse (in years), T_{max} and T_{min} is the time of maximum and minimum solar cycle near T_{ecl} , respectively. T_{max} identified from WDC-SILSO data and T_{min} identified from SWPC NOAA. Phase of solar activity ϕ changes from -1 to 1 and can be interpreted as the phase of solar cycle from maximum to maximum. [8] obtained a linear fitting equation for the maximum monthly sunspot number (W_{max}) with flattening index (ϵ) when approaching the minimum solar cycle using data from 60 events of TSE. This prediction equation has large 1σ -uncertainty (± 65) due mainly to the large sensitivity of the flattening index value to many factors, such as number of innermost isophotes selected for linear approximation, possible error in the orientation of coronal images, etc.([8])

$$W_{max} = -2.8 + 466.1\epsilon \quad (3)$$

By using Equation 3, the maximum amplitude of the monthly sunspot numbers for the next solar cycle can be calculated. We also compared our results of the coronal flattening index, TSE phase, and W_{max} with other studies.

3. Results and Discussion

The north-south direction of the four TSE 2016 observation images were rotated by 66° clockwise (Figure 1: Left panel) to get the proper orientation and matched with reference images (see Section 2)



Figure 1. Left panel: TSE image is superimposed on the relevant X-ray image from SDO/AIA193 (inner) and streamer structure from SOHO/LASCO to confirm the exact rotation. Middle panel: Example of the white-light corona during 2016 TSE from our observation with $f/5.6$ aperture and $1/60s$ exposure. Right panel: isophotes images with marking line for measurement of flattening index .

Twenty isophotes in various solar radius obtained from these four images. Then each of the isophotes calculates its coronal flattening index using Equation 1 (Figure 1: Right panel). Coronal flattening index for various solar radius from 20 isophote are plotted and shown in Figure 2. The isophotes construction is limited to the distance of $1.7R_{sun}$ due to low signal to noise ratio outside this distance. To overcome this limitation, Ludendorff coronal flattening index at $r = 2R_{sun}$ is extrapolated using the linear equation $\epsilon = 0.0471R_{sun} + 0.061$ obtained from linear regression as displayed in Figure 2. Ludendorff coronal flattening index for 2016 TSE is 0.16.

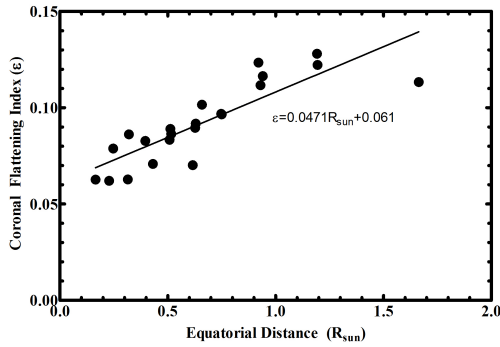


Figure 2. Coronal Flattening Index of the solar corona during 2016 TSE.

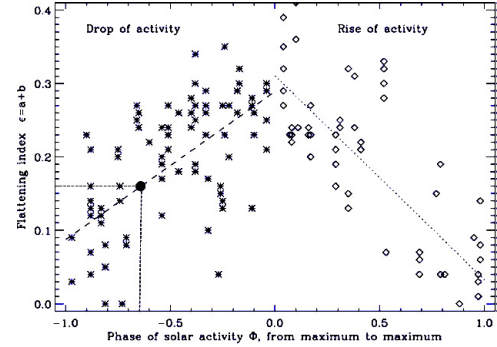


Figure 3. Dependence of the flattening index on the phase of solar activity [8]. Result of TSE 2016 shown in black dot mark.

The 2016 TSE corona phase for 24^{th} solar cycle then calculated using Equation 2. The peak time (in year) of the 24^{th} solar cycle (T_{max}) based on data from WDC-SILSO Royal Observatory of Belgium, Brussels, the maximum monthly sunspot number for the 24^{th} solar cycle is 146.1 which occurred in February 2014 ($T_{max} = 2014.123$). While the 24^{th} solar cycle minimum based on multi-year predictions of monthly sunspot numbers from NOAA SWPC occurred in December 2019 with the monthly sunspot number values is 4.1, so $T_{min} = 2019.923$. And for the eclipse time (T_{ecl}) occurred on March 2016 is 2016.206. 24^{th} solar cycle phase then calculated using

Equation 2, obtained $\Phi = -0.64$. Keep in mind that the solar cycle phase Φ value is determined by the prediction of T_{min} which might be still get corrected. The value of ϵ and ϕ for TSE in 2016 were added to the plot of coronal flattening index and the solar cycle phase which compile based on the 60 TSE events from 1851 to 2010 as presented in the Figure 3.

Figure 3 shows that 2016 TSE occurs when solar activity went to its minimum value hence the observed corona is a pre-minimum type corona. Also the 2016 TSE corona shapes are nearly symmetric based on the flattening index value despite a fairly large streamer near the solar south pole on 2016 TSE which affects the solar poles diameter but in this case, does not really influence the final value of the coronal flattening index.

Furthermore, the prediction for maximum amplitude of the sunspot numbers for 25th solar cycle obtained by using Equation 3. So the predicted of maximum sunspot number for the 25th solar cycle (W_{max}) is 70 ± 65 . The flattening index factors used to predict the maximum amplitude sunspot numbers for the next cycle can be regarded as an indirect characteristic of the solar poles magnetic field [8]. Our result means that the 25th solar cycle activity is predicted to be lower than the current cycle, which has peaked in February 2014 with a sunspot number value of 146. This can be compared with results from other studies. For example, Li et al. [11] stated that the next solar cycle will reach maximum on October 2023 with amplitude of 109 which is inside 1σ -uncertainty of our calculated amplitude. Rigozo et al. [12] also gave slightly higher predicted maximum amplitude of sunspot number in cycle 25 which is 132. This maximum value will be reached on April 2023. Javaraiah [13] used long-term record of the sunspot groups area to study the solar cycle behavior. The implication of that study is the predicted maximum amplitude of 25th solar cycle which is as low as 50 ± 10 .

4. Conclusion

The coronal flattening index is 0.16 and the 24th solar cycle phase is -0.64 based on 2016 TSE observations. This results suggest that the corona is a pre-minimum type. This gives the predicted maximum of the monthly sunspot number for the 25th solar cycle to be 70 ± 65 . Therefore, the solar activity for 25th solar cycle is predicted to be lower than current solar cycle.

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